Ocean Acoustics and Signal Processing for Robust Detection and Estimation

Zoi-Heleni Michalopoulou
Department of Mathematical Sciences
New Jersey Institute of Technology
Newark, NJ 07102

Telephone Number: (973) 596 8395
Fax Number: (973) 596 5591
E-mail: michalop@njit.edu

URL: http://www.math.njit.edu/~elmich
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LONG TERM GOALS

The long term goal of this project is to develop efficient inversion algorithms for successful estimation and detection by incorporating (fully or partially) the physics of the propagation medium. Algorithms will be designed for geoacoustic inversion and also for robust ASW localization and detection.

OBJECTIVES

- Achieve accurate and computationally efficient source localization by designing estimation schemes that combine acoustic field modeling and optimization approaches.
- Develop methods for passive localization and inversion of environmental parameters that select features of propagation that are essential to model for accurate inversion.

APPROACH

Arrival times and amplitudes of distinct frequencies (within a single mode or across different modes) provide a wealth of information on environmental properties of the propagation medium and source location. The role of modal arrival times and amplitudes in geoacoustic inversion and source localization has been discussed in [1, 2, 3, 4].

Typically, extraction of modal information from the reception of signals that have traveled long distances in dispersive underwater environments is performed with time-frequency or wavelet analysis [5]. Accurate identification of modes and their amplitudes and arrival times is, however, challenging. The uncertainty in the process has an impact on the accuracy of geoacoustic inversion and source localization, which has not been, to date, quantified.

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14. ABSTRACT
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15. SUBJECT TERMS

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A method was developed by the PI and her research group in 2008 for modal decomposition of a received signal and modal arrival time estimation. The method employed principles of dynamical systems for multiple source tracking [6] and applied those to the extraction of "frequency trajectories" from spectrograms of received signals [7, 8, 9]. Every mode in the short time Fourier transform representation of the signal is treated as a distinct source track with small changes in location (frequency, in our case) at each time step. We generated a particle filter that exploits two relationships, one for frequency updating vs. time (state equation) and the second one for comparison of the Fourier transform representation of a synthetic signal for the chosen state to that of the true signal (observation equation). After a few initial steps, the particle filter identified distinct "tracks" and reported probability distributions around them. The method also estimated the number of tracks (modes) present at each time using a stochastic mechanism that allowed modes to "be born" or expire.

The approach provided more reliable estimates than conventional short-time Fourier transform analysis; furthermore, it allowed the computation of posterior probability distributions for arrival times which can be used for uncertainty estimation in geoacoustic inversion. However, the method is resolution bounded since it uses spectrograms as the reference for modal decomposition.

To expand and improve on this work, we investigated how the observation equation of our filter can be improved and used Smoothed Pseudo Wigner-Ville Distributions (SPWVD) to model the time-frequency characteristics of broadband receptions. Wigner-Ville time-frequency distributions provide accurate information on signal dispersion with high resolution [10]. Smoothing the distributions removes cross-modal interference terms (with a resolution penalty). Similar to [1], we modeled in [11] the SPWVD distributions at selected times t as sums of shifted and scaled sinc functions with the help of the stationary phase approximation. The centers and amplitudes of the sincs were related to modal frequencies and amplitudes. We then built a Gibbs Sampler to optimize the modal decomposition process, estimating arriving modal frequencies, corresponding amplitudes, and the number of modes present in the data.

In parallel, we explored how similar approaches can improve arrival time estimation; the ultimate goal is again accurate inversion, where the uncertainty in arrival times provides insight into the uncertainty in geometry/environment characterization (work done in collaboration with Rashi Jain, Ph.D. student, ONR Graduate Traineeship Award recipient). We developed and improved a particle filter-based approach where we jointly estimate arrival times at a set of hydrophones, taking into account possible variations of arrival times at spatially separated phones. This process allows us to substantially reduce the error in arrival time estimation and facilitates the calculation of probability distributions for these arrivals (which are not always Gaussian as often assumed in inverse problems). The developed approach has been applied successfully to real data.

WORK COMPLETED

The described estimation approaches were designed and applied to synthetic and real data. For the dispersion analysis, we worked with the Gulf of Mexico data. The sound had propagated through a shallow water medium with a thin layer of sand over limestone; the frequency content of the signals was between 100 and 600 Hz. For the arrival time estimation of short-range multipath arrivals, we simulated signals received at a set of vertically separated receivers at a relatively small distance (~1000 m) from the source and used the Haro Strait data set. More tests are underway with Haro Strait, Gulf of Mexico, and Shallow Water 06 data sets.

In addition to modal arrival time estimation from dispersion analysis, inversion was conducted using the estimates of the particle filter tracking approach. Geometry, bathymetry, and sound speed inversion was carried out, employing the multipath arrival times extracted with our technique.

RESULTS

Modal Arrival Estimation

Figure 1 presents the SPWVD of a reception at one phone; the reception is from the Gulf of Mexico data. Superimposed on the distribution are the numerically calculated dispersion curves for an assumed propagation medium.

Figure 2(a) shows a slice of the SPWVD of Figure 1, and the maximum a posteriori modal combination using the developed Gibbs Sampler. Figure 2(b) demonstrates the posterior probability distributions for the arriving modal frequencies as computed via the Gibbs Sampler. Our method estimates that seven modes arrive at time t (the number of modes is also considered to be unknown). This is an interesting result, because visually only six modes appear present. The method, however, determines that the last modal peak is constructed from two arrivals. Careful analysis of the calculated dispersion curves of Figure 1 for the chosen time t shows that, at that time and at frequencies between 400 and 500 Hz, two modes arrive close to each other.

In addition to the estimated frequencies arriving at time t, our approach also provides probability distributions for modal amplitudes which can be used for attenuation estimation. Figure 3 demonstrates a joint posterior probability distribution for amplitudes of the first two arriving modes at time t.

Multipath Detection

Figure 4 demonstrates results from a particle filtering approach as applied to short-range time-series for arrival time estimation of distinct multipaths. The figure presents mean squared error in arrival time (in time samples) vs. number of particles for two different particle filtering techniques implemented here and compares this error to that from standard Maximum Likelihood (ML) estimation; two arrivals are estimated, direct and surface reflection. Arrival time error is much smaller with the dynamic methods, exploring spatial variability constraints across hydrophones. Performance is slightly better with the model labeled here as “velocity”, indicating that the rate of change of arrival time with space was taken into account in the dynamic relationship employed in our tracker. The gain in performance is more prevalent in lower Signal to Noise Ratios. Performance was further improved with smoothing techniques.

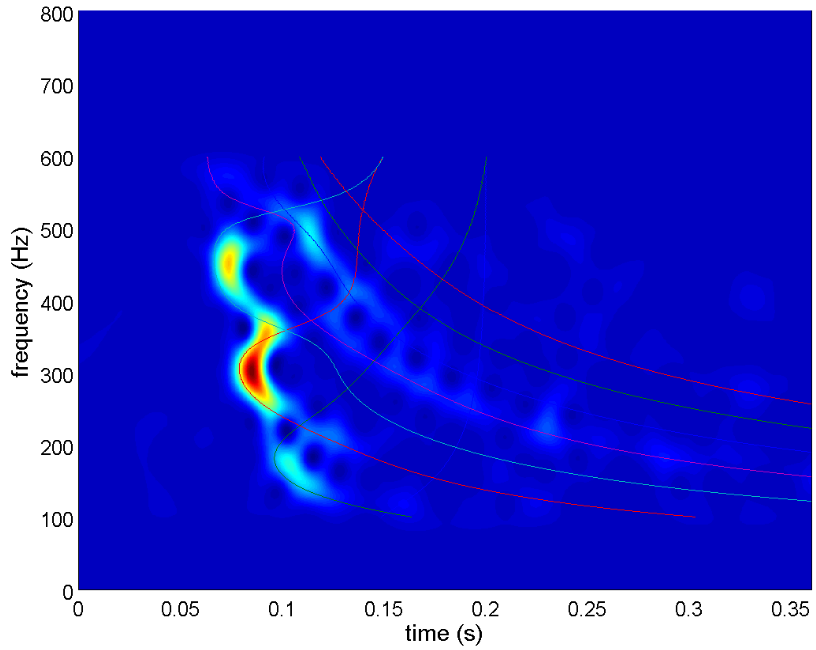

Figure 1: SPWVD of a signal that has propagated 21 km from the source in a shallow water environment (Gulf of Mexico data). The frequency content of the signal was between 100 and 600 Hz. Numerically calculated dispersion curves for an assumed environment are superimposed.

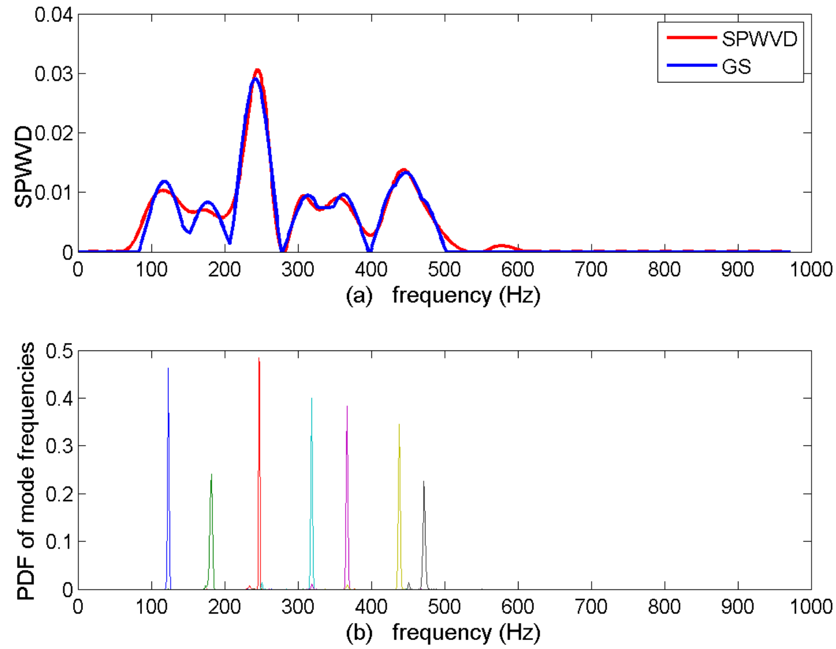

Figure 2: (a) A slice for a selected time t from the PSWVD of Figure 1 (red) and the MAP estimate for the modal decomposition as calculated by the Gibbs Sampler. (b) Posterior probability distributions of frequencies arriving at time t.

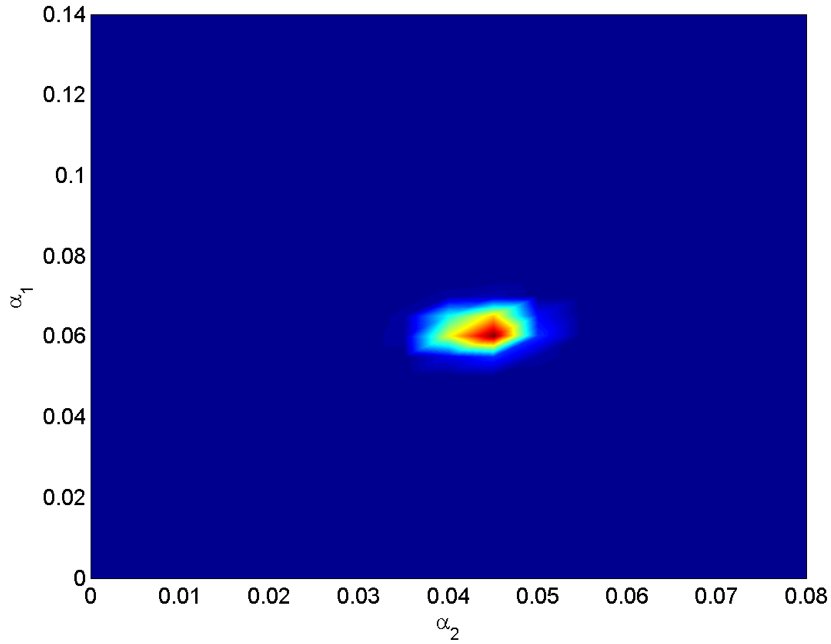

Figure 3: Joint posterior probability distribution for modal amplitudes 1 and 2 at time t.

IMPACT

The significance of accurate arrival time estimation in geoacoustic inversion has been extensively studied with several methods designed for producing geoacoustic parameter estimates and measures of the uncertainty in the estimation process. The reliability of these methods is intimately tied to the ability of accurately extracting and identifying arrival times. The new methods facilitate this extraction and the association between paths/modes and detected arrivals and also produce posterior probability distributions of modal frequencies or arrival times. These can then be employed to quantify uncertainty in the estimation of geoacoustic parameters.

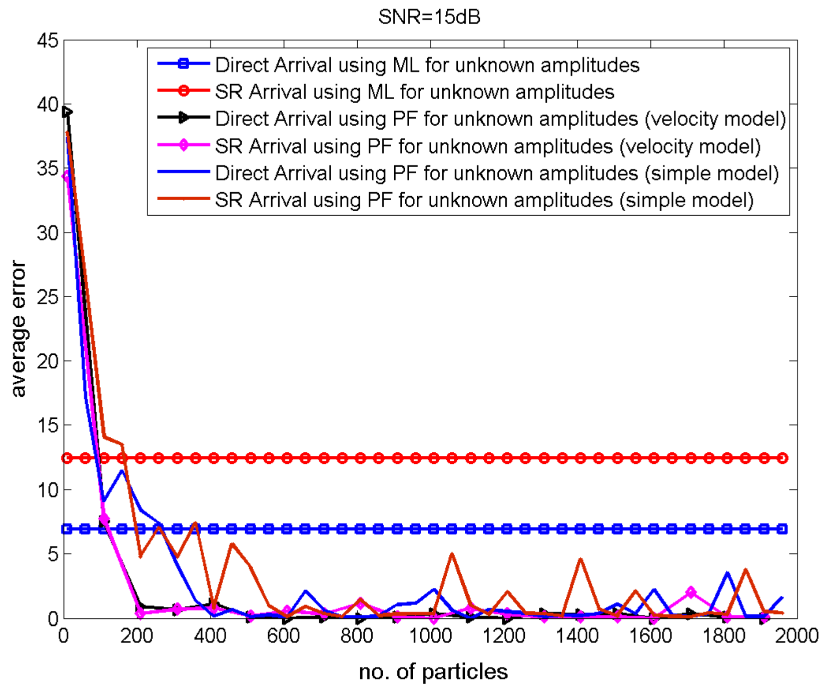

Figure 4: Arrival time error for two particle filtering approaches and standard ML estimation for an SNR of 15dB.

RELATED PROJECTS

A collaboration is underway with Dr. Lisa Zurk (Portland State University) on tracking as it relates to the waveguide invariance principle [12].

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PUBLICATIONS

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HONORS/AWARDS

- NJIT College of Science and Liberal Arts Service Award, 2009.